

# Numerical Modeling of Urban Air Temperature

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**Abstract** This paper is devoted to provide an understanding of the urban warming phenomenon by analyzing the urban surface and air temperature variation profiles. The aim is to investigate the temporal variation of air temperature of different urban locations in Trivandrum city. Various methods adopted in the present study include theoretical analysis, field measurements and numerical simulation. Using the basic heat transfer equation, temporal variation of temperature was evaluated at each nodal point after discretizing the domain. Finite difference scheme was employed for the calculations and a numerical code was developed in Mat-lab for the evaluation of temperature.

**Keywords** - Heat transfer equation, Finite difference scheme, discretization.

## I. INTRODUCTION

Urbanization is the physical growth of urban areas as a result of the development processes which have become inevitable in the present decades. The urbanization process alters the thermal characteristics of the surface, which significantly impact the surface energy balance within the atmospheric boundary layer. One of the serious problems associated with it is the distinct urban climate due to the replacement of natural land surface by artificial structures including roads, buildings and other infrastructure, along with the anthropogenic heat and pollution emission from transportation and human activities. The phenomenon of the urban air temperature being remarkably warmer than that of the surrounding rural areas is known as the urban heat island.

The urban heat island effect is a phenomenon where air temperatures in densely built cities are higher than the suburban rural areas. The primary cause of heat island in cities is due to the absorption of solar radiation by the building structures, roads and other hard surfaces during day time. The absorbed heat is then re-radiated to the surroundings and increases ambient temperatures at night. The warming that results from urban heat islands over small areas such as urban street canyons is an example of local climate

change. Street canyon is a typical configuration of densely built urban areas, consisting of a narrow street between buildings that lineup continuously along both sides. It has a different climate where microscale meteorological processes dominate.

The primary methods to study the thermal characteristics within the street canyon include field measurements, laboratory experiments, and numerical simulation. Field measurements offer lots of useful information for the studies related to Urban Heat Island. However, field measurements are limited by their low spatial resolution, high cost, and uncontrollable meteorological conditions. The laboratory physical experiments have also been extensively applied to understand this complex phenomenon. But they provide data only for a few number of discrete measurement points.

Comparing with the experimental methods, the numerical simulation, a relatively economic approach, allows us to visualize the air flow and temperature distribution where measurements are not available. It can provide more comprehensive information on temperature variation with high spatial and temporal resolutions. [21].

The UHI issue is very prominent in many of the developing tropical cities where the ambient air temperatures and solar radiation intensities are normally high. Mehdi Shahrestani et al. [10] did a field study of urban microclimate in London. The outcomes of this research revealed that the climatic parameters were significantly influenced by the attributes of urban textures. K. Niachou et al. [7] did an investigation of the impact of urban environment on the potential of natural and hybrid ventilation in an urban street canyon in Athens, Greece. This study focused on the experimental investigation of thermal characteristics of a typical street canyon, oriented in ESE–WNW direction, under hot weather conditions. Their results indicated that the air temperature distribution inside a street canyon is a function of canyon geometry and orientation, as well as, of the optical and thermal properties of building and street materials and ambient weather conditions. Furthermore, the understanding of the

specific thermal characteristics is essential for the understanding of airflow inside the canyons. Runming Yao et al. [15] studied the urban microclimates in Chongqing, China using historical weather data, transverse measurement and numerical simulation. Two complementary types of field measurements were conducted: fixed weather stations and mobile transverse measurement. Numerical simulations using a house-developed program were able to predict the urban air temperature in Chongqing. The present study is devoted to provide a further understanding of the urban warming phenomenon by analyzing the urban surface and air temperature variation profiles. The aim is to investigate the temporal variation of air temperature of different urban locations in Trivandrum city. Various methods adopted in the present study include theoretical analysis, field measurements and numerical simulation. Using the basic heat transfer, temporal variation of temperature was evaluated at each nodal point after discretizing the domain. Finite difference scheme was employed for the calculations and a numerical code was also developed in Mat-lab for the same.

**II. METHODOLOGY**

The temperature variation in the atmosphere is basically due to the heat transfer mechanism. In this study the temperature variation is analysed using numerical modeling. The important steps in the numerical modeling of any physical process are: (i) problem definition, (ii) mathematical model with necessary boundary conditions, (iii) formation of numerical grid, (iv) discretisation of partial differential equation, (v) computer simulation. The modeling process involves the representation of the physical reality by a mathematical model: the governing equations of the problem. The basic heat transfer equation is considered for the temperature variation. The general heat transfer equation is:

$$\frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) + \dot{g} = \rho C \frac{\partial T}{\partial t} \dots\dots\dots(1)$$

T=temperature (°c), k=thermal conductivity, ḡ=heat generated, ρ=density, C=specific heat

For numerical simulation the system domain has to be divided into various nodal points i.e. numerical grid generation.

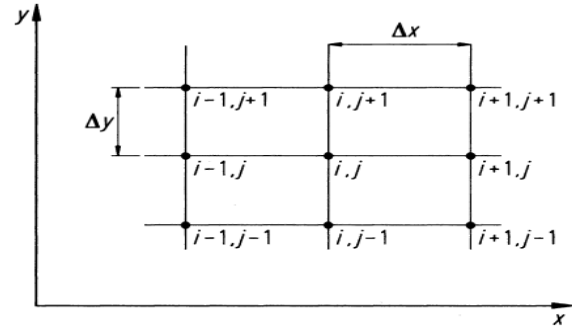


Figure 1: Numerical grid

The three classical choices for the numerical solution of PDEs are the finite difference method (FDM), the finite element method (FEM) and the finite volume method (FVM). The FDM is the oldest and is based upon the application of a local Taylor expansion to approximate the differential equations. In FDM, the partial differential equations obtained can be solved either by forward difference, backward difference or central difference method. The two dimensional transient heat conduction equation in finite difference form is:

$$\frac{\rho C_p}{k} \frac{T_{i,j}^{t+\Delta t} - T_{i,j}^t}{\Delta t} = \frac{T_{i-1,j}^t - 2T_{i,j}^t + T_{i+1,j}^t}{\Delta x^2} + \frac{T_{i,j-1}^t - 2T_{i,j}^t + T_{i,j+1}^t}{\Delta y^2} \dots\dots\dots(2)$$

$$\frac{\rho C_p}{k} = \alpha \dots\dots\dots(3)$$

$T_{i,j}^{t+\Delta t}$  is the temperature of node (i,j) for the time step t+Δt;  $T_{i,j}^t$  is the temperature of node (i,j) for time step t;  $T_{i-1,j}^t$  is the temperature of node (i-1,j) for time step t;  $T_{i+1,j}^t$  is the temperature of node (i+1,j) for time step t;  $T_{i,j-1}^t$  is the temperature of node (i,j-1) for time step t;  $T_{i,j+1}^t$  is the temperature of node (i,j+1) for time step t. Δx and Δy is the distance node (i,j) in horizontal and vertical distances. Δt is the time interval.

Number of equations will be obtained for each node simultaneously solutions for which will be started with the application of boundary conditions. The analytical solution for such equations will be hideous so computer based program is necessary in such situations.

A field experiment was conducted in order to understand the temperature profile inside an urban street. For the analysis of temperature variation within an urban air column, 2 D transient heat transfer equation was used in the urban road cross-section. Boundary conditions are the temperatures of buildings on both sides along with pavement surface and ambient air temperature on the top. The urban areas selected are medical college junction, SMV

junction and Pattom junction in Trivandrum city. A cross-section of the urban air column was selected between the buildings separated by the road. The two-dimensional transient heat transfer was analysed using finite difference method

and the ambient air temperature were monitored. Equation (2) is used to evaluate the temperature variation. It is assumed that  $\Delta x = \Delta y = 3m$ ,  $\Delta t = 1$  hr and  $\alpha$  is the thermal diffusivity value of air, then the equation becomes

$$T_{i,j}^{t+\Delta t} = \kappa \left[ T_{i-1,j}^t - 2T_{i,j}^t + T_{i+1,j}^t + T_{i,j-1}^t - 2T_{i,j}^t + T_{i,j+1}^t \right] + T_{i,j}^t \dots\dots\dots(3)$$

Table I

A sample Data collected from Medical college junction on 10/06/2015

Time	temp at point on left building(°C)	temp at point on right building(°C)	temp at point on pavement t(°C)	ambient air temp(°C)
8:00 AM	58	57	68	28.6
9:00 AM	60	61	70	29.1
10:00 AM	63	64	72	29.4
11:00 AM	64	65	74	29.5
12:00 PM	66	66	77	29.9
1:00 PM	68	69	82	30.3
2:00 PM	70	71	83	30.4
3:00 PM	69	69	84	29.9
4:00 PM	67	68	83	29.6
5:00 PM	64	66	81	29.1
6:00 PM	62	64	78	28.7

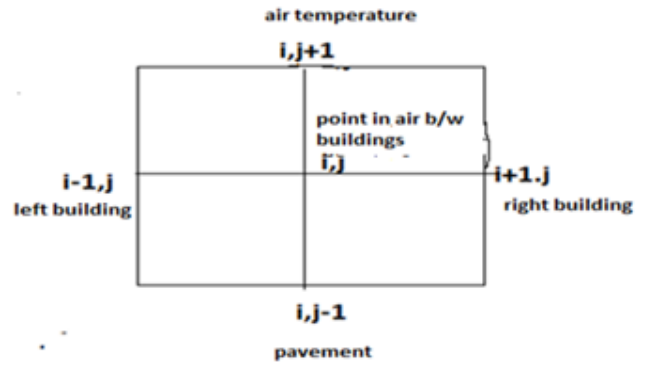


Figure 3: Representation of node

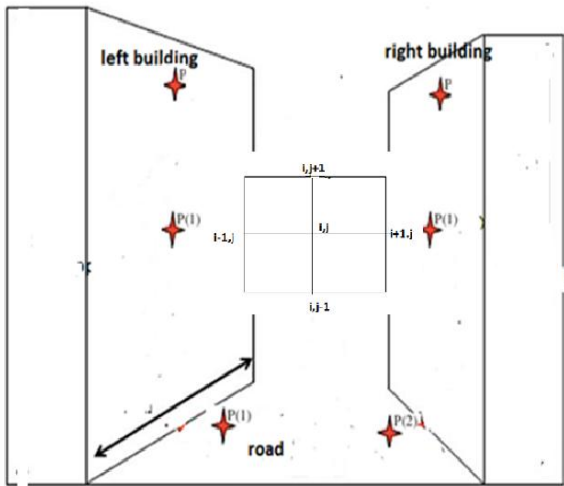


Figure 2: A cross-sectional view of an urban street

The temperature variation of the point in between the two buildings is analysed using two dimensional heat transfer equation and based on the assumptions made. The solution was obtained both analytically as well as using mat-lab. The calculated values were then compared with the observed values.

III.RESULTS & DISCUSSIONS

The calculations were done using 2 D transient heat conduction equation in finite difference scheme. The comparison of obtained results from analytical method as well as using mat-lab with the measured values is given below.

The following assumptions were made for the study:

- The temperature of the vertical air profile near to the buildings is same as that of the building temperature
- The temperature of the horizontal air profile near to the pavement is same as that of the pavement temperature
- Temperature in the air column at the middle section is assumed to be the ambient air temperature

To evaluate the variation of air temperature in the selected urban cross-section, the temperature on the pavement surface, buildings on both sides of the road

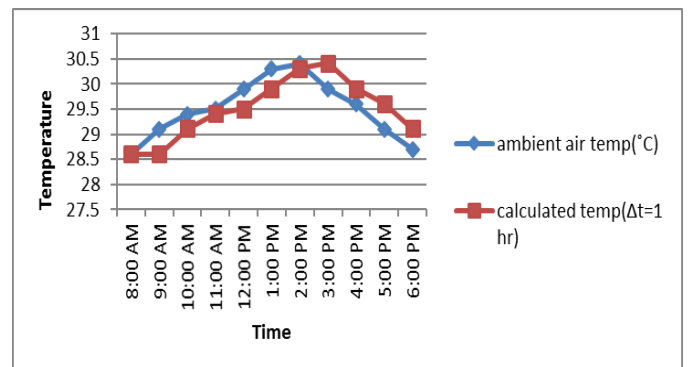


Figure 4: Comparison of measured and calculated measured temperature at medical college

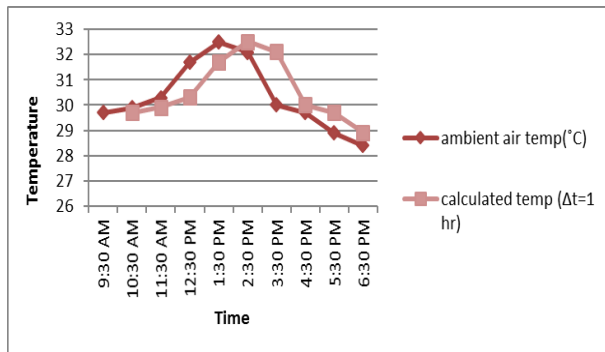


Figure 5: Comparison of calculated and measured temperatures at SMV junction

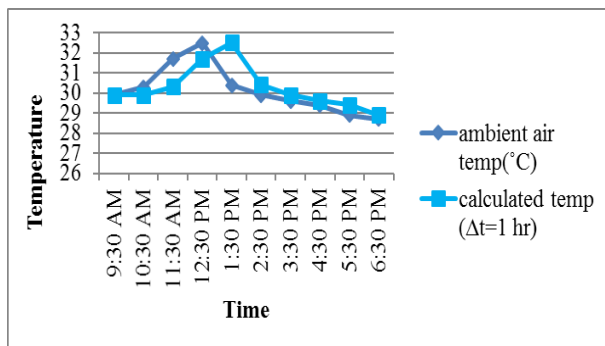


Figure 6: Comparison of calculated and measured temperature at Pattom junction

#### IV. CONCLUSIONS

A field study was conducted on selected urban roads in Trivandrum city with buildings on both sides to simulate 2 D heat conduction with known boundary condition. The temporal variation of temperature was predicted by the numerical code developed and was validated with actual field values. The trend of diurnal temperature was similar in all selected urban roads. The calculated values show a decrease during morning session and an increase during evening session when compared with the measured values. This trend may be due to the reason that the numerical calculation for the next time step is purely dependent on the temperature values of previous time steps. The ambient air temperature is dependent on many other meteorological parameters which are not included in the numerical calculations. And also the measurements were carried out in the monsoon season during which there was a sudden variations in the temperature.

#### V. SCOPE OF THE STUDY

In this study heat transfer due to conduction was only considered. The experiment can further be expanded using the other modes of heat transfer. The study can provide better results if the air temperature

was evaluated considering the other meteorological parameters like relative humidity, rainfall etc. Temperature evaluation was carried out within an urban cross-section using finite difference method in the present study. More accurate results will be obtained if a control volume of air is considered for which finite volume method can be used.

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